AD A032733

CRREL REPORT 76-37

Airborne resistivity and magnetometer survey in northern Maine for obtaining information on bedrock geology

DDC
RECEIVED
NOV 29 1976
B

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Measuring the resistivity of granitic rock at VLF with the Geonics EM16R ground unit. (Photograph by David Atwood.)

CRREL Report 76-37

Airborne resistivity and magnetometer survey in northern Maine for obtaining information on bedrock geology

P.V. Sellmann, S.A. Arcone and A. J. Delaney

October 1976

D D C
RECEIVED
NOV 29 1976
B

Prepared for
U.S. ARMY ENGINEER DIVISION, NEW ENGLAND
By
CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Approved for public release; distribution unlimited.

ACCESSION for
NTIS White Section ☒
DDC Buff Section ☐
UNANNOUNCED ☐
JUSTIFICATION ....
BY ....
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
A

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (14) CRREL-[redacted]76-37	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) AIRBORNE RESISTIVITY AND MAGNETOMETER SURVEY IN NORTHERN MAINE FOR OBTAINING INFORMATION ON BEDROCK GEOLOGY.		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Paul [redacted]V. Sellmann, Steven [redacted]A. Arcone [redacted] Allen [redacted]J. Delaney		8. CONTRACT OR GRANT NUMBER(s) (12) 33p.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) DA Project 4A762719AT24 Task A2, Work Unit 003
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Division, New England Waltham, Massachusetts 02154		12. REPORT DATE (11) Oct[redacted]76 (12) A2
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

(9) Rept for Sep-Oct 75,

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Partially funded by Directorate of Military Construction, Office, Chief of Engineers, Washington, D.C. 20314

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aerial surveys	Geophysics
Allagash, Maine	Structural geology
Electrical resistivity	Subsurface investigations

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Geophysical studies were conducted during September and October of 1975 in northern Maine to locate rock types suitable for construction purposes for the proposed Dickey-Lincoln School Dam Project. Simultaneous airborne magnetometer and VLF electrical resistivity surveys were performed over an area of approximately 920 km^2 surrounding the confluence of the St. John and Allagash rivers. The resulting data were used to construct contour maps of apparent resistivity and of total magnetic intensity above the earth's background magnetic field. During the same time period, ground and multi-elevation surveys were performed over a special test sector of known geology. The ground and airborne study in the test sector aided in interpretation of the data by revealing a strong correlation

next page

20. Abstract (cont'd)

cont.

between igneous geology, resistivity, and magnetic intensity. Lack of a similar correlation between resistivity and magnetic data in the remainder of the survey area suggested an absence of additional areas of igneous rocks. The multi-elevation survey of the test area indicated that changes in flight altitude, necessitated by the topographic relief encountered, would not seriously affect the regional resistivity patterns. Although there was no strong evidence of igneous rocks outside the test sector, suitable rock types may exist within the Dss geologic unit (cyclically bedded gray slate and sandstone) in the central part of the main survey area, where most of the high resistivity contours occur.

PREFACE

This report is a presentation and analysis of the electrical resistivity and magnetometer airborne surveys flown in September and October of 1975 in coordination with the proposed Dickey-Lincoln School Dam Project in northern Maine. It was prepared by Paul V. Sellmann, Geologist, of the Northern Engineering Research Branch, Experimental Engineering Division, and by Steven A. Arcone, Geophysicist, and Allan J. Delaney, Physical Sciences Technician, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The Foundations and Materials Branch of the U.S. Army Engineer Division, New England funded the research. Previous CRREL participation in this project includes investigation of the surficial geology of the area and tectonic activity of the region (McKim and Merry 1975).

The airborne surveys were flown by Barringer Research Ltd. of Toronto, Canada, under contract to the New England Division of the U.S. Army Corps of Engineers. The multi-elevation surveys and ground studies were supported by DA Project 4A762719AT24, *Design, Construction and Operation Technology for Cold Regions*, Task A2, *Soils and Foundation Technology for Cold Regions*, Work Unit 003, *Electromagnetic Methods for Subsurface Exploration* (QCR 1.07-CARDS 114). Upon completion of the surveys all data, maps, flight records, photography, and daily logs were sent to CRREL where further processing, evaluation, and geologic interpretations and correlations were performed.

Pieter Hoekstra and Frank Jagodits technically reviewed the manuscript.

The contents of this report are not to be used for advertising or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

Simultaneous airborne magnetometer and VLF resistivity surveys were conducted in northern Maine to locate rock types suitable for construction purposes. This was done for the New England Division of the U.S. Army Corps of Engineers in response to anticipated requirements for the proposed Dickey-Lincoln School Dam Project. The surveys covered approximately 920 km^2. In addition, a small, special test area of known bedrock geology was surveyed to establish specific ground correlation and to examine the effects of flight altitude upon resolution.

Over the special test area both the contoured magnetometer and resistivity data differentiated the known igneous geology from the surrounding slate. Resistivity data obtained by ground VLF methods correlated well with the airborne resistivity results. The magnetic data indicated a normally expected degree of magnetic mineralization associated with the granodiorite and syenite in the test area, which can contain magnetite as an accessory mineral (Boone 1962). The multi-elevation surveys were flown at mean flight altitudes of 150 m and 300 m. The general distribution of anomalies at the higher altitudes remained unchanged, although detail was decreased. These results implied that local changes in altitude occurring during this survey would not cause any significant loss in resolution. In general, the test area results ensured the reliability of the overall survey and established a basis for airborne identification of igneous rocks for this study.

The data from the entire survey indicated the following results:

1) No other resistivity anomalies occurred with values as high as those associated with the igneous rocks of the test area.

2) No magnetic anomalies were found outside the test sector.

3) The more resistive areas outside the test sector corresponded with a cyclically bedded gray slate and sandstone unit in the central part of the survey area.

4) The resistivity data corresponded well with mapped reconnaissance geology of the region (Boudette et al. 1966).

From these results it was concluded that no new sources of igneous rocks are apparent. Rocks most suitable for construction purposes near the dam site may occur in the central part of the survey area, which is associated with areas of high resistivity.

AIRBORNE RESISTIVITY AND MAGNETOMETER SURVEY IN NORTHERN MAINE FOR OBTAINING INFORMATION ON BEDROCK GEOLOGY

P.V. Sellmann, S.A. Arcone and A.J. Delaney

INTRODUCTION

Knowledge of the distribution and quality of bedrock within the area of the proposed Dickey-Lincoln School Dam Project is important for development of construction plans and environmental impact statements. At the conception of this study known sources of rock suitable for construction purposes were of limited extent, since the most common rock type in the area is slate. The most suitable rocks are part of a remotely situated intrusive body more than 19 kilometers from the proposed dam site. Background geologic information is available from a regional reconnaissance study and a detailed investigation of the known intrusive complex (Boudette et al. 1966, Boone 1962). Based on these studies the New England Division of the Corps of Engineers (NED) felt that additional data were required to determine if unknown sources of rock suitable for construction purposes could be located nearer the project sites. As a result, CRREL was approached to determine if resistivity techniques could be used as an aid in obtaining this information.

In March 1975 a preliminary study was made to determine if resistivity contrasts of known rock types in the region were great enough to justify an extensive ground or airborne survey using the radiowave resistivity technique at VLF (very low frequency) which is the frequency range best suited for a bedrock study. It indicated that contrasts in the electrical properties between the intrusive rocks and other rock types in the area were great enough to permit this method to be considered for the proposed purpose, as well as for providing additional general information on bedrock properties (Sellmann et al. 1974, 1975). As a result of this work CRREL recommended that additional field investigations were warranted, and both an airborne resistivity and magnetometer survey were contracted. The surveys were used to complement each other, providing both electrical and magnetic property data for the rock types as well as a means of detecting magnetic mineralization.

The extent of airborne survey coverage was jointly determined by NED and CRREL project personnel (Fig. 1). Because of the large size and irregular shape of the total reservoir impoundment limits, complete airborne survey coverage was not practical or considered necessary. With the emphasis of this project placed on obtaining bedrock data, the more central part of the area near the proposed major construction activity was covered in detail. For control purposes these limits were also adjusted to include all previously mapped major rock types. Other factors influenced shape, e.g. the minimum practical length of flight lines, which is approximately 16 km, and the spacing of flight lines. A flight line spacing of 0.4 km was used for this study, in contrast to a tenth of a mile used on some previous surveys (Hoekstra et al. 1974).

In areas outside the main survey, pairs of magnetometer profiles were flown along the drainage networks. Only magnetometer data were obtained, since these can be acquired independently of flight line orientation, while resistivity lines must be flown at a fixed orientation for maximum coupling with the remote VLF transmitter.

During the first week of the airborne survey extensive ground measurements were performed in a special test sector of known bedrock geology, shown

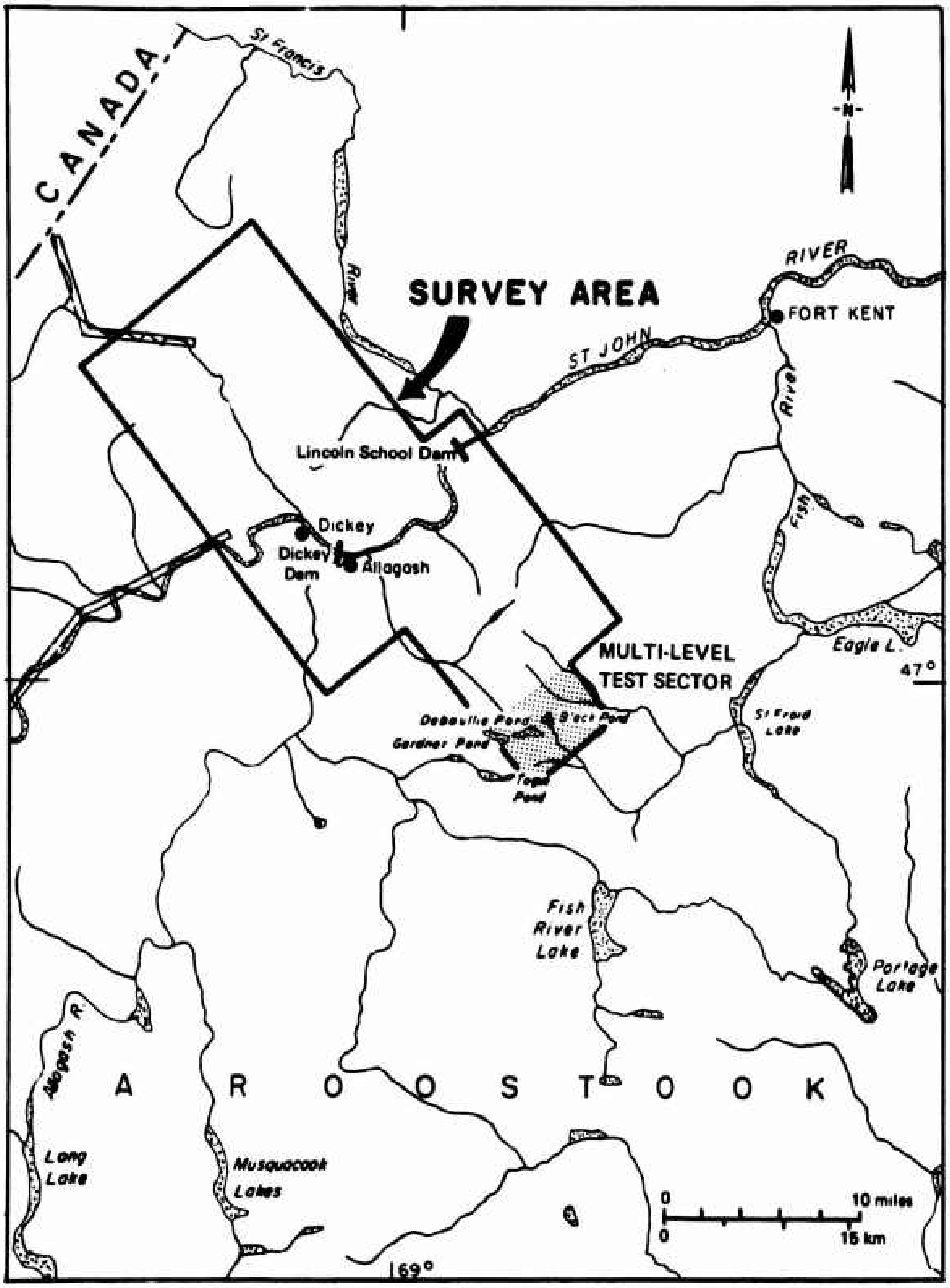
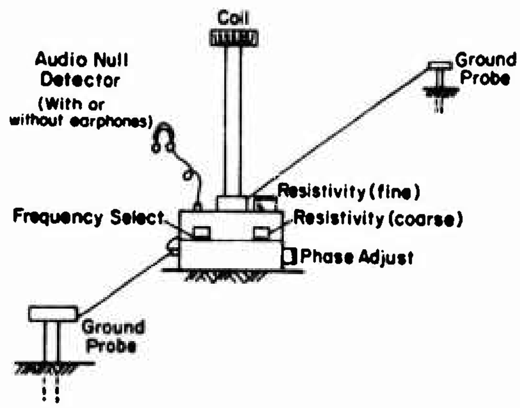
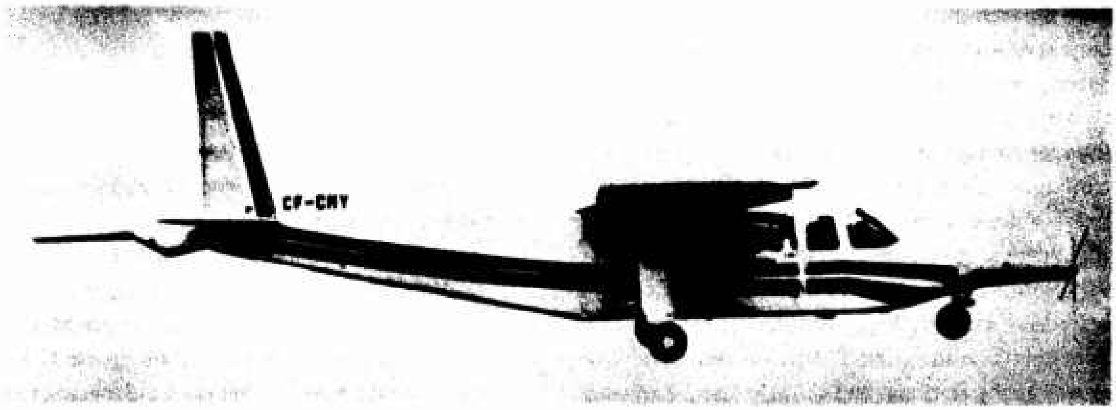


Figure 1. Index map showing the extent of airborne coverage. The survey area was flown with both the resistivity and magnetometer systems. Pairs of magnetometer lines were flown along the major drainage networks.



a. Ground unit (Geonics EM16R) for measuring resistivity at VLF by using the surface impedance method.



b. STOL aircraft with E-PHASE antennas in the nose cone and a magnetometer sensor extended to the rear (photograph courtesy of Barringer Research Ltd.).

Figure 2. Systems for measuring resistivity at VLF.

in Figure 1. In addition two separate surveys in this sector were conducted at mean altitudes of 150 and 300 m. These special studies were made to verify the quality of the entire airborne survey, with respect to both rock type differentiation and the effect of flight altitude upon resolution of resistivity anomalies.

MEASUREMENT TECHNIQUES EMPLOYED

Ground

A commercially available Geonics EM16R ground unit for measuring resistivity, illustrated in Figure 2a and on the cover of this report, was used for monitoring the VLF transmitter (NAA, 17.8 kHz) located near Cutler, Maine. The instrument is calibrated directly in apparent resistivity and phase for the particular frequency desired. The measurement is performed by determining the ratio of E_x (the horizontal electric field), measured between two probes spaced at 10 m and oriented in a radial direction towards the transmitter, and H_y (the horizontal magnetic field), measured with a small coil near the ground surface orthogonally to E_x. Since no current need flow from the ground to the probes the system is virtually free of contact resistance problems.

The coil is used to find the direction to the station, and the correct apparent resistivity values are found by tuning for an inaudible null with both the resistivity (i.e. amplitude) and phase dials. The accuracy of the instrument depends upon distance to the transmitter, as great distances can cause much noise and limit the null detection. Since Cutler, Maine, is within 300 km of the survey sight and operates at a radiated power of 1 MW, noise was not a limitation.

Airborne

The Barringer Research Ltd. E-PHASE* system was used for the aerial survey (Barringer 1972-73).

* *E-PHASE is the trade mark of the Barringer Ltd. system.*

This system employs a Britton Norman Islander, a short takeoff and landing (STOL) aircraft, specially modified to include a nose stinger on which horizontal and vertical dipole antennas are mounted as shown in Figure 2b. The E-PHASE system is capable of monitoring as many as four frequencies. For this survey only one frequency was used, station NAA (17.8 kHz), located near Cutler, Maine. The survey was flown with an average flight line orientation of 55° (true azimuth) for an average coupling angle of 80.5° with the transmitter. The survey altitude of the aircraft varied around 150 m. The mean flight line spacing was 0.4 km.

Airphoto mosaics and/or topographic maps were used for navigation. A flight path camera obtained continuous photographic coverage along the flight lines. Reference points (fiducials) were placed in the flight path recovery photography and at corresponding locations on data stored on an analogue (pen trace) recorder. Manually triggered fiducials were used to note points on the ground, such as streams and lakes, as well as the start and end of flight lines. Each day the flight path recovery film was developed, and recorded data were printed and inspected by Barringer Research Ltd. to ensure that all information was obtained. In the case of missing or unusable photo coverage, malfunction of the instrumentation, or transmitter problems, portions of lines or entire flights were flown again (Barringer 1975).

Additional information on the E-PHASE system, such as calibration, navigation and data reduction, has been discussed by Hoekstra et al. (1974) and by Palacky and Jagodits (1975). A review of the theory of electromagnetic resistivity surveying is given in Appendix A.

Magnetometer survey

A special tail stinger was installed on the survey aircraft to accommodate the magnetometer sensor. The airborne magnetometer, which records variations in the earth's magnetic field, and the reference ground base unit, measuring the total field, both utilize the principle of proton precession. A Barringer Research airborne AM-104 proton precession magnetometer was used to determine the variations of the earth's magnetic field. The resolution of this instrument is 1 gamma,* with a cycling rate of 1.1 s. The magnetic data were recorded on an analogue recorder and on magnetic tape.

A GM-123 field proton precession magnetometer, manufactured by Barringer Research Ltd., was located at Madawaska, Maine (32 km east of Ft. Kent) and used as the station magnetometer. During magnetic storm activity, which occurred between 6 and 8 October 1975, the surveying was suspended.

In Appendix B a brief review of magnetic surveying is given.

RESULTS

Ground control study

During the airborne survey of the test sector ground control was established by measuring the apparent resistivity and phase by the surface impedance method. Readings were made every 60 m along the traverses shown in Figure 3, which are superimposed upon the bedrock geology as mapped by Boone (1962). The traverses primarily followed old logging roads, except for line A which cut along the steep ridges of Gardner Mountain. A few sample readings were taken at the pond shores where the apparent resistivity invariably dropped to less than 200 ohm-m.

The first three columns of Table I present a statistical summary of the data collected over the various rock types. Bedrock was rarely more than several meters below the surface along all of these traverses. The large dispersions in the resistivities, noted by the standard deviations in parentheses, primarily result from variations in bedrock properties. The highest resistivities were obtained over the intrusive rocks. Dispersion in phase was largest for the slate, with readings varying from 3° to 54°. Over the intrusive rocks the phase quickly stabilized, as indicated by the decrease in standard deviation.

For direct comparison of the results of the ground and airborne surveys, the ground data must be modified, based on the same assumptions used in calculating the airborne values. The ground data are recomputed using only the quadrature component of the surface impedance and an assumed phase angle of 45° (eq A2, App. A). A normalized distribution of the modified ground data is plotted in Figure 4, showing a clear distinction between the slate and intrusive rocks in the control area. (A summary of the modified data is provided in the last column of Table I). The

* *1 gamma = 1 x 10^{-9} tesla.*

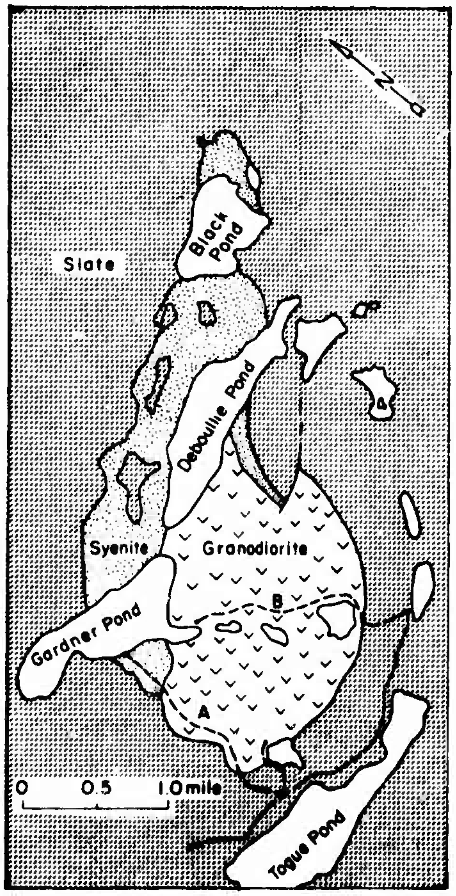


Figure 3. Ground control traverses along which surface impedance measurements were made, shown superimposed upon the bedrock geology as mapped by Boone (1962).

Table I. Apparent resistivity data obtained during ground survey. The last column presents modified ground resistivity values, based on the assumptions used in calculating airborne values. Standard deviations for the data are shown in parentheses.

Bedrock type	*Number of samples*	*Mean apparent resistivity (Ω-m)*	*Mean phase (°)*	*Mean quadrature resistivity (Ω-m)*
Seboomook slate	94	5481 (0.89)	23.93 (0.43)	1871 (0.85)
Granodiorite Section A	22	9009 (0.44)	28.86 (0.15)	4374 (0.47)
Granodiorite Section B	35	7086 (0.70)	35.90 (0.17)	4597 (0.62)
Syenite	8	5937 (0.56)	43.25 (0.11)	5342 (0.53)

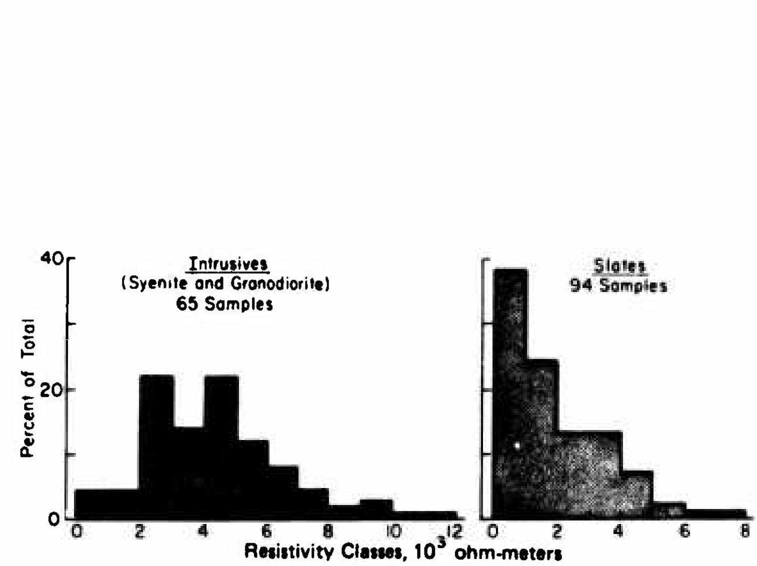


Figure 4. Normalized distribution of the ground data showing a clear distinction between the slate and intrusive rocks.

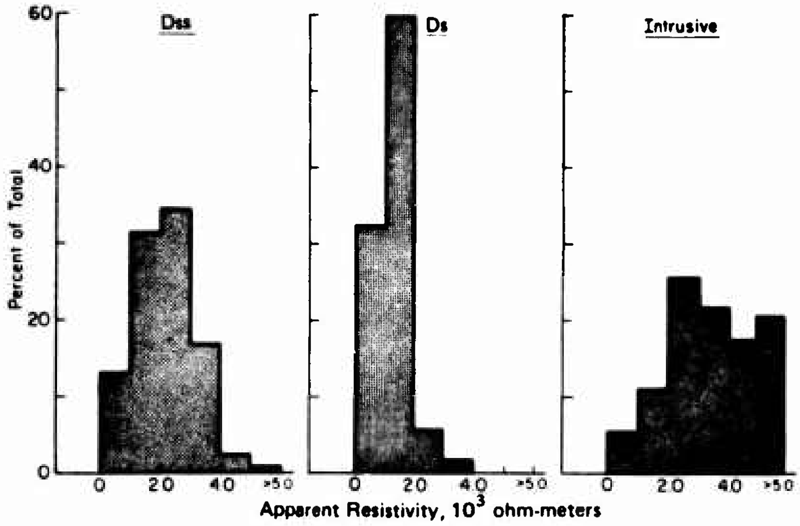


Figure 5. Airborne resistivity data for the various mapped rock types (Dss-cyclically bedded gray slate and sandstone, Ds-gray slate and minor graywacke). Values were obtained by sampling at regular intervals along the flight lines.

suppression of values for the slate is due to the low range of phase values caused by the till cover and/or the extremely high permittivity of slate (Parkhomenko 1967).

When resistivity values in Figure 4 and the last column of Table I are compared to those obtained along the flight lines of the airborne survey shown in Figure 5, the agreement may be seen between the ground and airborne observations. Slate values in Figure 4 should be compared to values for the same rock type, shown as Ds values in Figure 5.

The rapidly changing topography in the whole survey area made it unfeasible to always maintain a constant altitude. Therefore, as mentioned previously, a multi-elevation test was conducted in a small test sector to determine the effect of survey altitude, necessitated by topographic changes, upon resolution. Two separate surveys were flown at mean altitudes of 150 m and 300 m, both surveys containing the same number of flight lines.

In Figure 6 the comparisons between the contoured data from both surveys can be made. The general distribution of resistivity anomalies remains unchanged while the detail has decreased at the higher altitude. At this higher altitude there is a greater emphasis of the 4000 ohm-m contour over the intrusives, which is in near agreement with the mean values in the last column of Table I and is indicative of the averaging effect of altitude.

In general an excellent level of correlation was found between the airborne and ground readings for the test sector, ensuring the quality of the remaining resistivity survey.

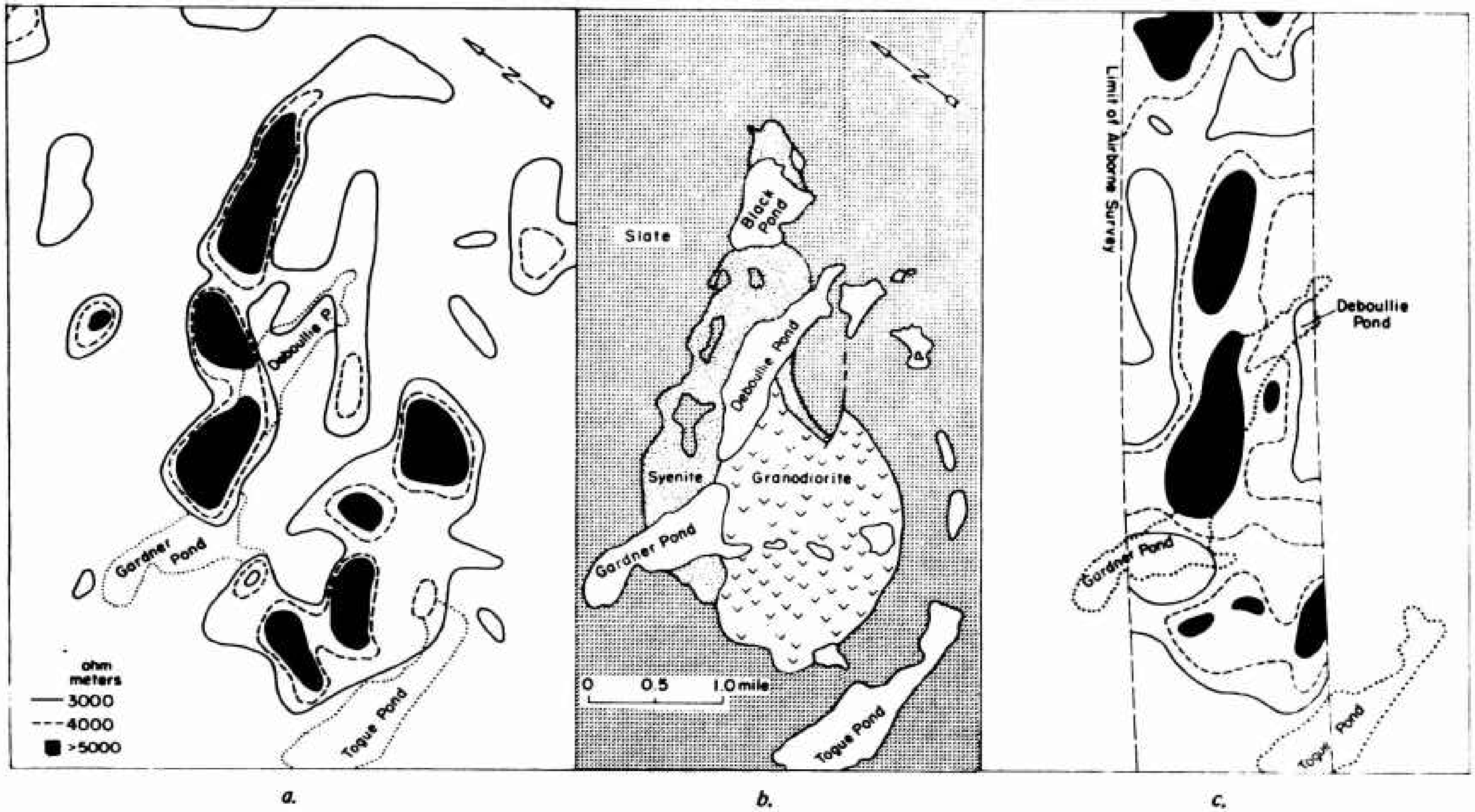


Figure 6. Multi-level contoured VLF apparent resistivity contours over the Gardner Mountain stock. The bedrock geology as mapped by Boone (1962) is shown in the center (b). Airborne measurements were taken at 150 m (a) and 300 m (c).

No ground studies were conducted for the airborne magnetometer survey, since past research and employment of this technique have already established its value.

VLF survey

The most noticeable features of the VLF data are the numerous tightly clustered, closed-contour resistivity highs shown in Figure 7. This pattern reflects the complicated surficial and bedrock geology of the area. In general the highest resistivity areas are associated with areas of major relief. This correlation is based on the fact that these are the locations where the conductive till is the thinnest and values reflect the generally more resistive bedrock which is near the surface. A generalized topographic map is provided (Fig. 8) as an aid in illustrating that the bedrock types can best be examined in areas of greatest relief. Virtually all the areas of high resistivity (> 3000 ohm-m) agree with units mapped as bedrock, or bedrock with a till cover, in the earlier surficial geologic study conducted by CRREL (McKim and Merry 1975).

A quantitative demonstration of these observations is shown in Table II. The table gives the distribution of areas with greater than 3000 ohm-m resistivity in relation to the topographic features they contain. Seventy-three areas were delineated, none containing only a valley. Approximately 70% of the areas contained only flanks and/or ridges.

Table II. VLF apparent resistivity contours greater than 3000 ohm-m.

Topographic situation	*Number*	*Percentage*
Ridge	14	19.2
Flank	17	23.3
Ridge and flank	20	27.4
Ridge, flank and valley	16	21.9
Flank and valley	6	8.2
Valley	0	0
Totals	73	100.0

It is also apparent from a comparison of Figure 7 and Figure 8 that many mountainous areas are also of relatively low resistivity (< 3000 ohm-m). Therefore, the lack of conductive overburden is not a major influence upon resistivity distinctions within these areas. The most plausible explanations for the resistivity distinctions among mountain types are the following:

1) There is a difference in bedrock type.

2) Certain flights passed directly over mountain peaks where it is known (Harrison et al. 1971) that the vertical electric field increases because of the sharp features, thereby suppressing resistivity values.

The second explanation is applicable to individual peaks such as in the Hafey, Gardner, and Deboullie mountains. Along these high elevations, ground readings (granodiorite Section A in Table I and Sellmann et al. 1975) that were modified for comparison to the airborne method indicated a suppression of airborne values. However, most flightlines in mountainous areas passed over the flanks, rather than peaks.

Bedrock geology and resistivity

When the reconnaissance bedrock geology of this area (Boudette et al. 1966 and Boone 1962) is examined, general distribution patterns become apparent. As shown in Figure 9, in the central part of the study area the bedrock units occur in broad bands, while to the northern end of the area these bands become more contorted and narrow, including a greater contrast in rock types. A large intrusive rock unit occurs near the southern limit of the area.

The southern and central parts of the region were characterized by three main units of lower Devonian age. The southernmost unit, Ds, was defined as gray slate and minor graywacke. The southern limit of this slate unit is not mapped, but it probably extends beyond the limits of the bedrock reconnaissance study, to the southern extent of the present study. The central part of the area was mapped as a cyclically bedded gray slate and sandstone (Dss). North of this unit another lower Devonian unit (Dsg), composed of graywacke and gray slate, was defined. North of these large units the structure becomes more complex and rock units range in age from Ordovician to Devonian. A greater range in rock types also occurs, including limestone, orthoquartzite, and siltstone. The intrusive body found in the southern part of the area is composed of granodiorite and syenite.

When the resistivity contours are placed upon Figure 9 several correlations become apparent. The highest resistivity values (> 6000) are associated with the intrusive rocks in the Gardner Mountain area. The next most obvious correlation is seen when areas of greater than 3000 ohm-m are examined. A belt containing


3000 ohm-meters
4000 ohm-meters
5000 ohm-meters

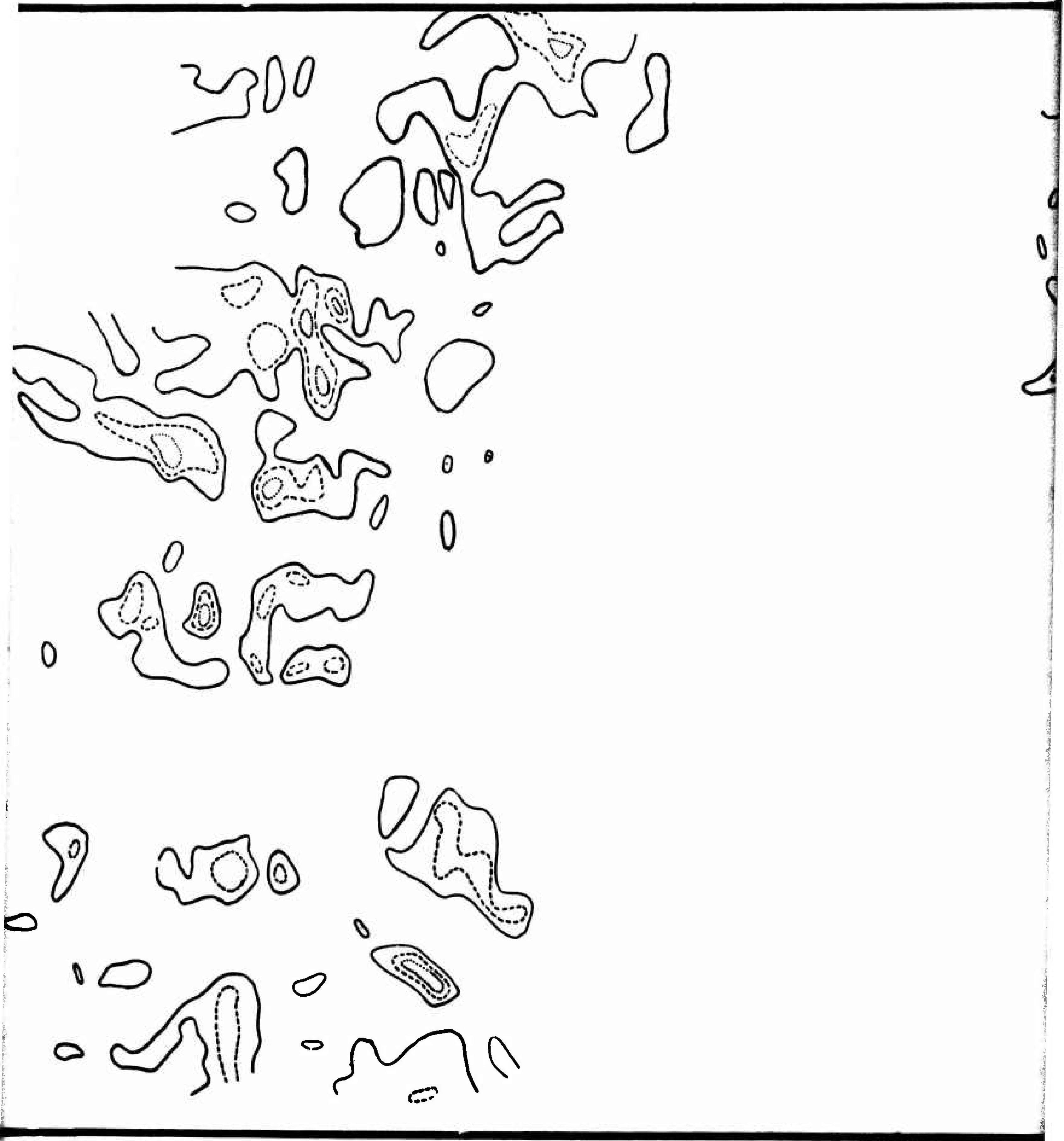


Figure 7. Generalized VLF apparent

2

...ure 7. Generalized VLF apparent resistivity contour map. Contoured values in ohm-meters.

3

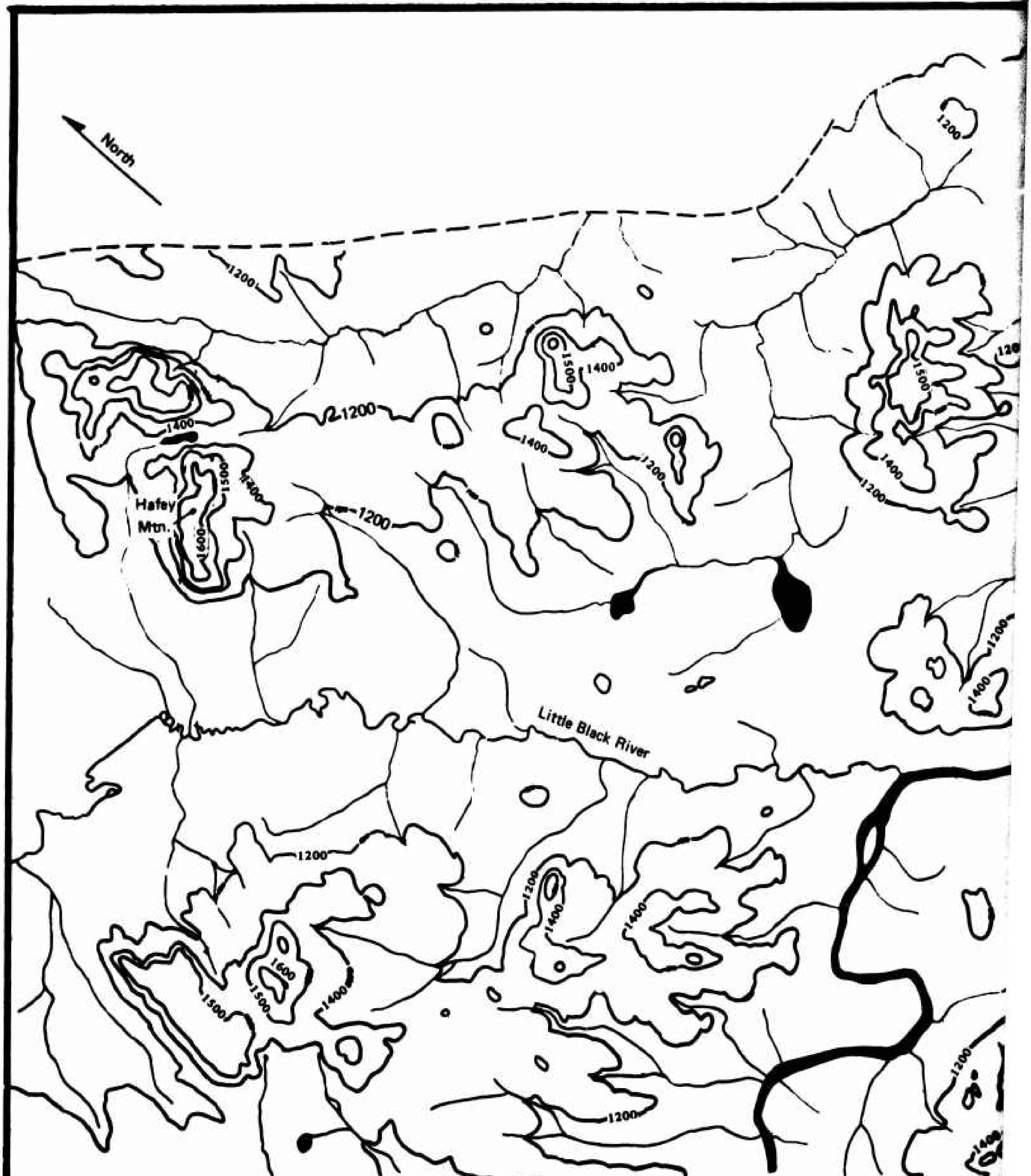
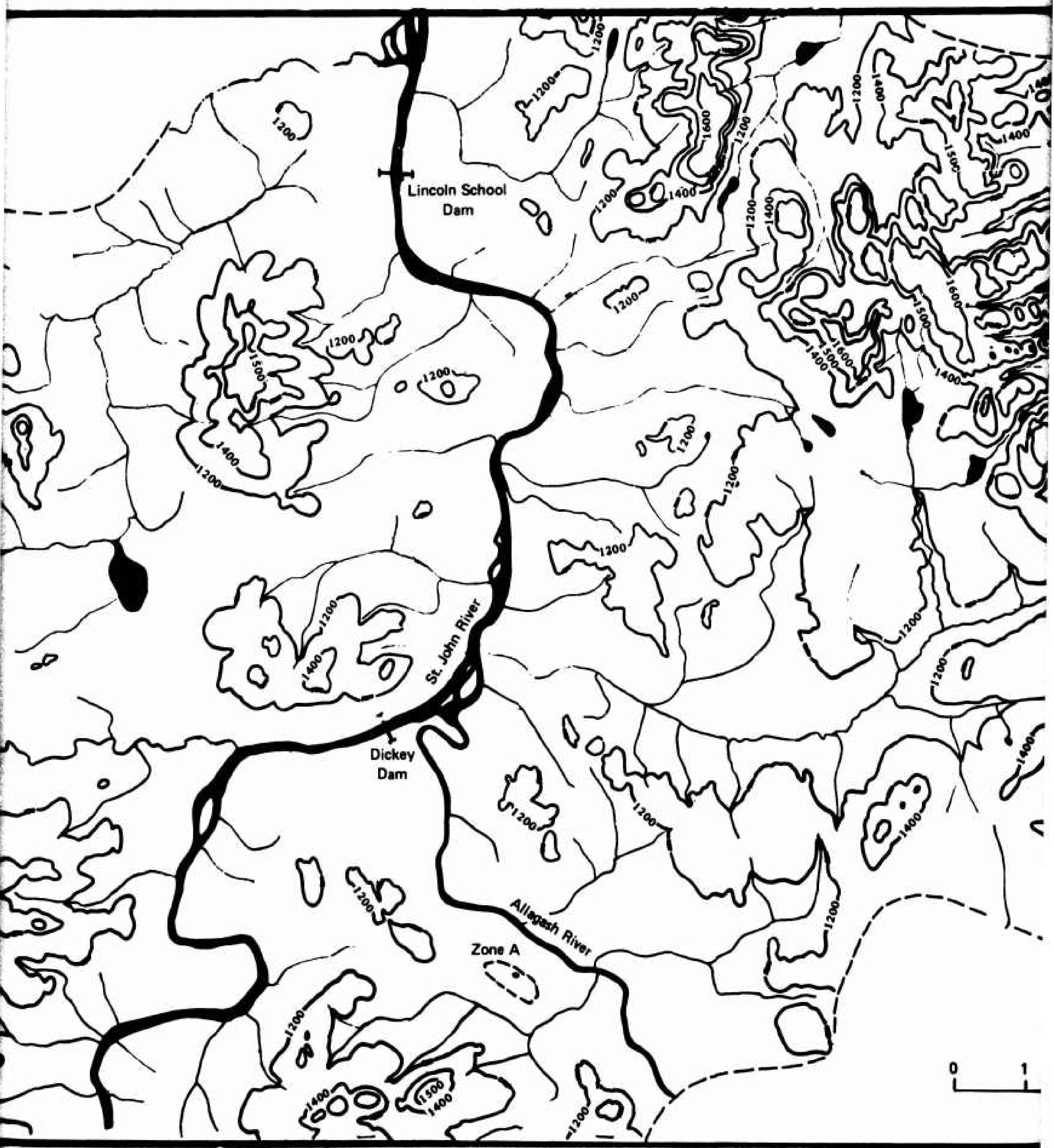
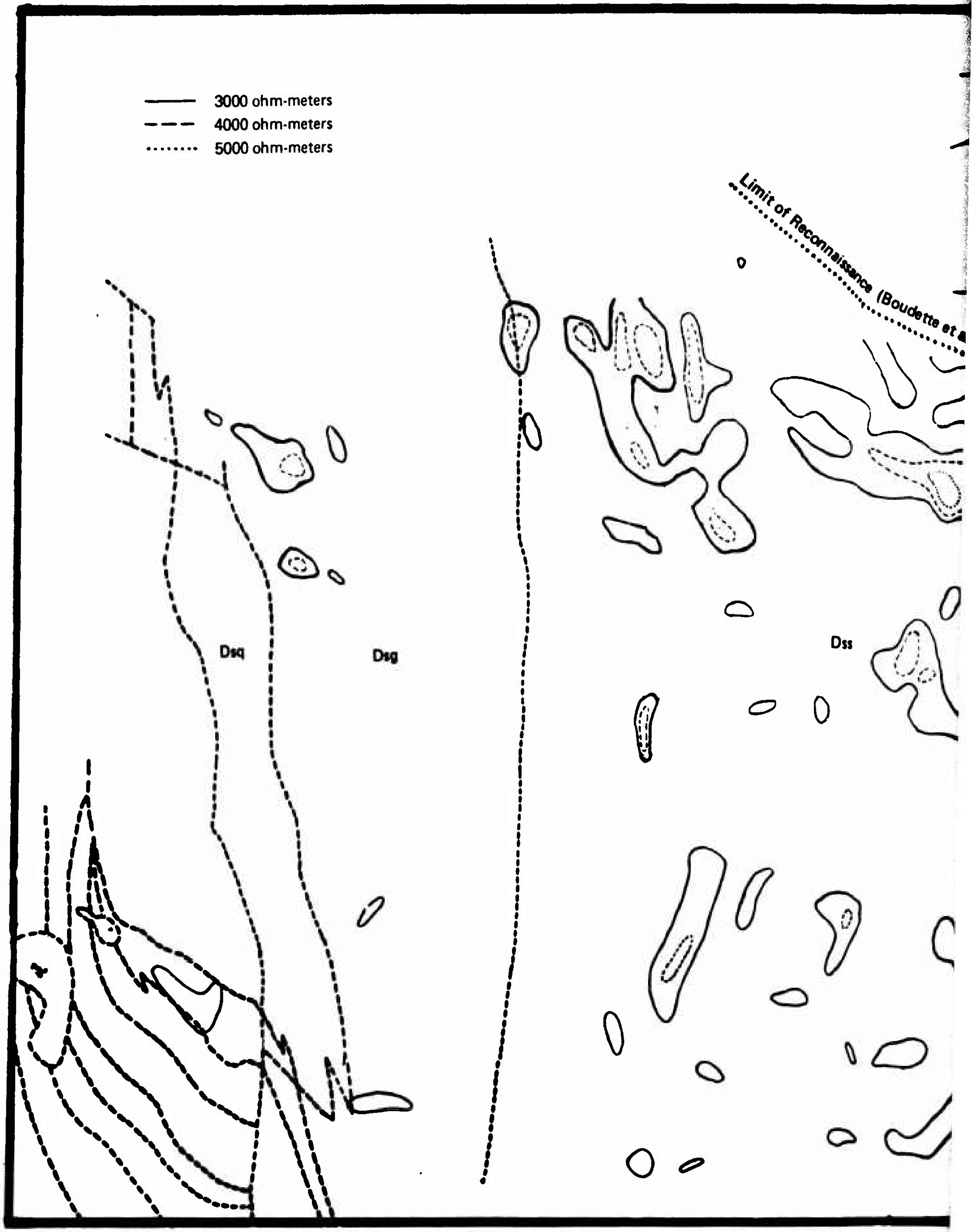
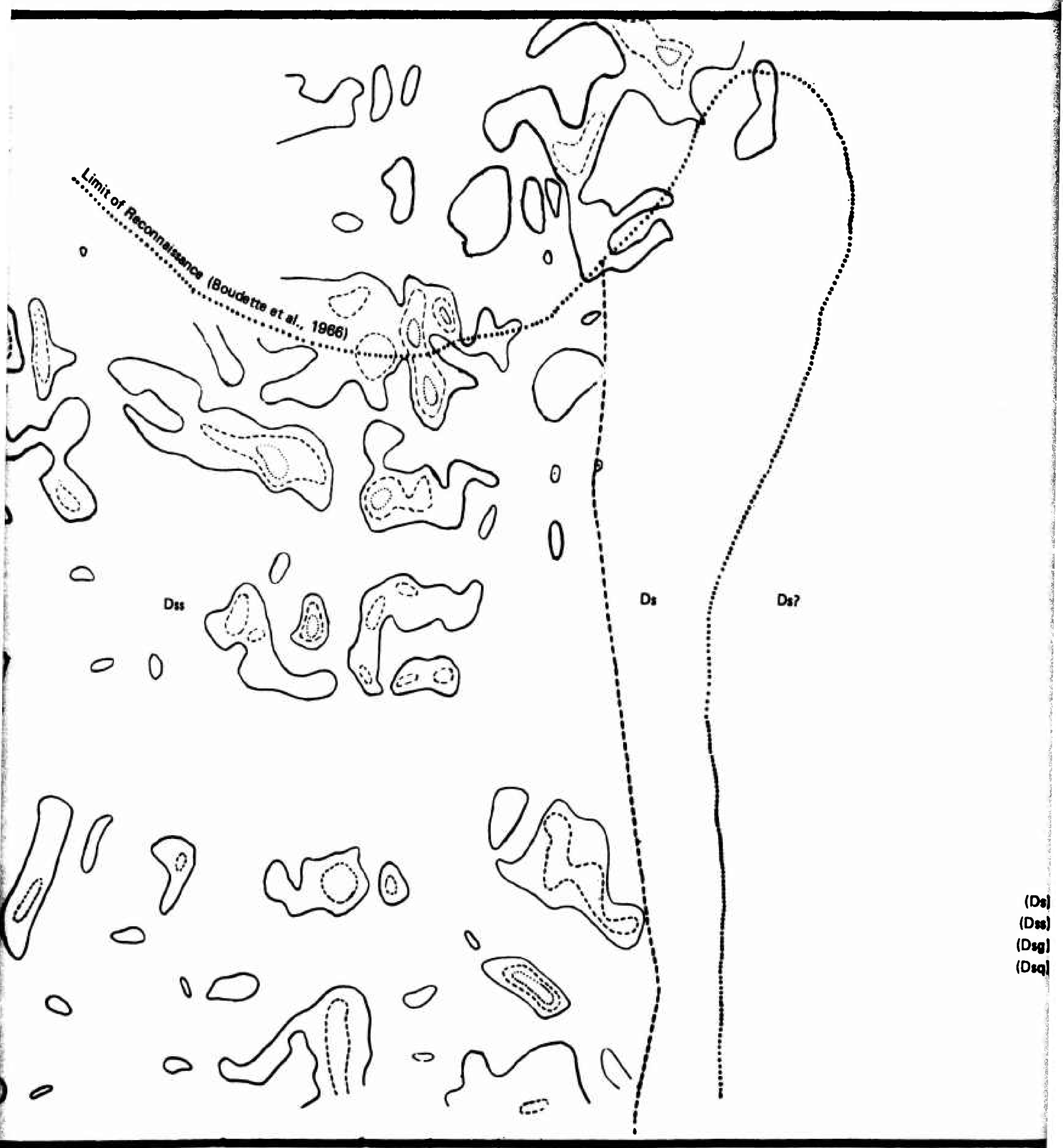


Figure 8. Generalized topographic map with selected contour intervals (ft) and drainage patterns (after USGS topographic maps, 1:62500 series).


Lincoln School Dam
Dickey Dam
St. John River
Allagash River
Zone A
1200
1400
1500
1600
0
1


1200
1400
1500
1600
Gardner Mtn.
0
1
2
3 Miles


3000 ohm-meters
4000 ohm-meters
5000 ohm-meters
Limit of Reconnaissance (Boudette et a
Dsq
Dsg
Dss



Limit of Reconnaissance (Boudette et al., 1966)
Dss
Ds
Ds?
(Ds]
(Dss]
(Dsg]
(Dsq]

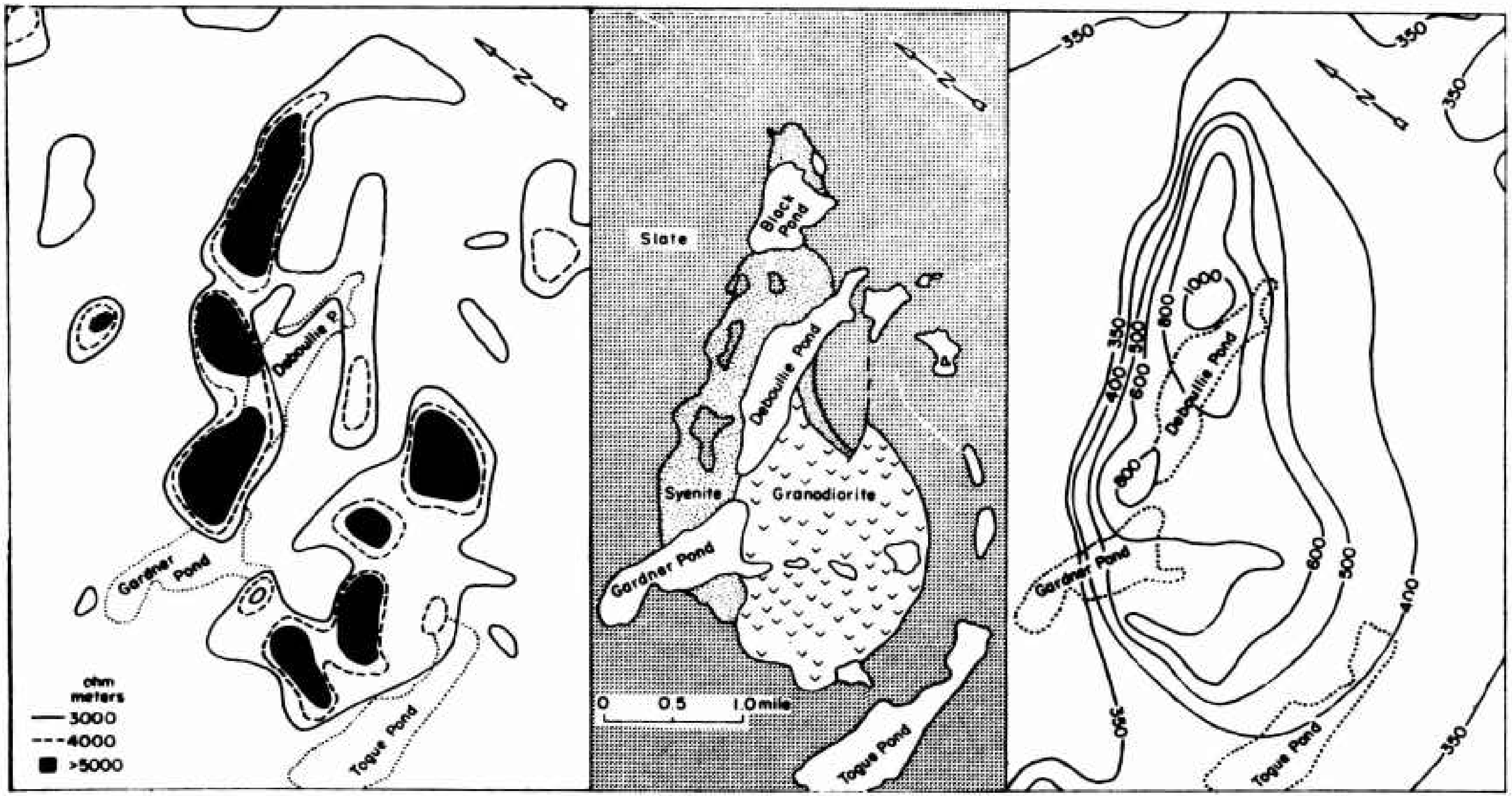
Figu

2

(Ds) Gray slate and minor graywacke
(Dss) Cyclically bedded gray slate and sandstone
(Dsg) Graywacke and gray slate
(Dsq) Orthoquartzite and minor sandstone

0 1 2 3 Miles

Figure 9. Bedrock distribution map (after Boudette et al. 1966, Boone 1962).



a. b. c.

Figure 10. VLF apparent resistivity (a) and magnetic contours (c) over the Gardner Mountain stock. The bedrock geology as mapped by Boone (1962) is shown in the center (b) for comparative purposes. (Magnetic contour values are in gammas above the background intensity.)

many high resistivity zones is noticeable in the central part of the study area, coinciding with the mapped limits of the Dss bedrock unit. In this belt, the high resistivities are found in areas of high relief. The values commonly exceed 3000 ohm-m and locally reach a maximum of 5500 ohm-m.

The remaining rock types, such as the Ds geologic unit, have very low resistivities, with few areas having values that exceed 3000 ohm-m. This occurs despite the wide range of rock types and large number of areas of high relief where bedrock is near the surface. The resistivity data from the Dss, Ds, and intrusive units in Figure 5 show these same trends. The intrusive unit with the highest resistivities, Dss, has more than 20% of its values greater than 3000 ohm-m while less than 2% of the values in the Ds unit exceed 3000 ohm-m.

Aeromagnetic survey results

The aeromagnetic survey did not outline anomalies usually associated with abnormally high magnetic mineralization in either the main study area or along flight line pairs flown along the major drainage networks. In general, the magnetic intensity data were featureless, with the only significant anomaly being associated with the known intrusive rocks in the southern part of the area. This anomaly is shown in Figure 10 for comparison to the resistivity data and the bedrock geology. Fifty-seven thousand gammas have been subtracted from all values to eliminate the background intensity of the earth. Modal analysis of the granodiorite and syenite (Boone 1962) indicated that magnetite is a common and, in some cases, abundant accessory mineral. This fact alone can account for this distinctive feature, although the patterns and intensities seen are considered normal for these rock types.

CONCLUSIONS

The combined results of the aeromagnetic and E-PHASE survey allow several conclusions to be drawn concerning sources of rock suitable for construction purposes. These conclusions are based on the fact that the most suitable rocks will be the most electrically resistive, with further distinctions based on mineralization to be inferred from the presence of magnetic data.

The conclusions are:

1. The highest resistivity values are associated with the known Gardner Mountain intrusives. This is also the location of the only significant magnetic anomaly. The correlation of the VLF and magnetic data in this area was shown in Figure 10.

2. The lack of similar resistivity-magnetic correlations in other locations suggests little or no other occurrence of these rock types.

3. Local resistivity highs in the Dss unit suggest locations for field study as possible sites of rock types suitable for construction purposes. The Boudette et al. (1966) study indicates this as an area of slate and sandstone. The distribution of these rock types is not known; therefore, it can only be assumed that the sandstones may be the most resistive rock type. No magnetic anomalies occur in this area.

LITERATURE CITED

Barringer, A.R. (1972, 1973) Geophysical exploration method using the vertical electric components of a VLF field as a reference. Canadian Patent no. 1,261,732: USA Patent no. 3,594,633 and 3,763,419.

Barringer Research Limited (1975) Operational report on the airborne resistivity E-PHASE and magnetometer surveys Allagash River area, Aroostook County, Maine.

Boone, G. (1962) Potassic feldspar enrichment in magma: Origin of syenite in Deboullie district, northern Maine. *Geological Society of America Bulletin*, vol. 73, p. 1451-1476.

Boudette, Hatch and Harwood (1966) Reconnaissance geologic maps of the St. John and Allagash river basins, Maine. U.S. Geological Survey.

Collett, L.S. and A. Becker (1967) Radiohm method for earth resistivity surveying. Canadian Patent no. 795919.

Culley, R.W., F.L. Jagodits and R.S. Middleton (1975) E-PHASE system for detection of buried granular deposits. *Proceedings, Symposium on Modern Innovations in Subsurface Exploration*, 54th Annual Meeting of the Transportation Research Board, Washington, January 1975.

Eliassen, K.E. (1956) A survey of ground conductivity and dielectric constants in Norway within the frequency range of 0.2-10 mc. Oslo: Geofs. Publ., vol. 19, no. 11, p. 1-30.

Frischknecht, F.C. (1973) Electromagnetic scale model studies of geophysical methods using a plane wave source. University of Colorado, Department of Electrical Engineering, Ph.D. thesis (unpublished).

Grant, F.S. and G.F. West (1965) *Interpretation theory in applied geophysics.* New York: McGraw Hill.

Harrison, R.P., J.L. Hecksher and E.A. Lewis (1971) Helicopter observations of very low frequency waves over certain mountains and shorelines. *Journal of Atmospheric and Terrestrial Physics*, vol. 33, p. 101-110.

Hoekstra, P. and A.J. Delaney (1973) Ground resistivity survey in the area of the Tennessee-Tombigbee Waterway. CRREL Special Report 191. AD 767246.

Hoekstra, P., P.V. Sellmann and A.J. Delaney (1974) Airborne resistivity mapping of permafrost near Fairbanks, Alaska. CRREL Research Report 324. AD A000694.

McKim, H. and C.J. Merry (1975) Use of remote sensing to quantify construction material and to define geologic lineations: Dickey-Lincoln School Lakes Project, Maine. CRREL Special Report 242.

Olhoeft, G.R. (1975) The electrical properties of permafrost. University of Toronto, Ph.D. thesis (unpublished).

Palacky, G.J. and F.L. Jagodits (1975) Computer data processing and quantitative interpretation of airborne resistivity surveys. *Geophysics*, vol. 40, p. 818.

Parkhomenko, E.I. (1967) *Electrical properties of rock.* New York: Plenum Press.

Sellmann, P.V., P. Hoekstra and A.J. Delaney (1974) Airborne resistivity near Fairbanks, Alaska: An aid in bedrock geology reconnaissance. CRREL Special Report 202. AD 777792.

Sellmann, P.V., A.J. Delaney and P. Hoekstra (1975) Radiowave resistivity measurements in northern Maine for identifying bedrock type. CRREL Special Report 238.

Wait, J.R. (1962) *Electromagnetic waves in stratified media.* New York: Pergamon Press.

Ward, S.H. (1967) Electromagnetic theory for geophysical applications. In *Mining Geophysics*, vol. 2, Society of Exploration Geophysicists, Tulsa, Oklahoma.

Waterways Experiment Station (WES) U.S. Army (1953) The unified soil classification system. Technical Memorandum no. 3-357, vol. 1, App. A, B (revised April 1960).

APPENDIX A. THEORY OF ELECTROMAGNETIC RESISTIVITY SURVEYING

RESISTIVITY SURVEYING

The physical property, electrical resistivity, spans a large range of magnitude. Values ranging from 10^{-7} ohm-m for metallic elements to 10^{10} ohm-m for some granitic rocks are well documented (Parkhomenko 1967). The most common range encountered in d.c. and electromagnetic surveying is approximately 10 to 10,000 ohm-m. Within this range fall many materials of economic and geologic importance that can be detected as a result of contrasts in resistivity with adjacent materials.

A primary influence on the resistivity of sediments is the amount of ions associated with adsorbed surface water on particles. Therefore, there is a correlation between resistivity and grain size. In some earth materials, such as crystalline rocks, a more important factor may be the amount of ions dissolved within the pore water. The general resistivity range for most earth materials is illustrated in Figure A1 (Culley et al. 1975, Hoekstra and Delaney 1973). Other factors, such as temperature, pressure and ice content, also influence resistivity but are not significant factors in the present study.

Radiowaves propagating over the earth's surface are influenced by the electrical properties of the subsurface materials. By comparing the various field components of the radio surface wave it becomes possible to obtain ground resistivity data.

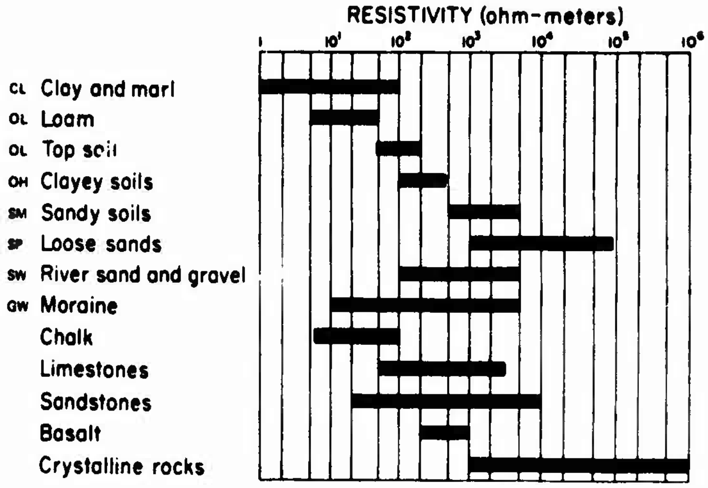
Since literature on the interaction between radiowaves and the earth is available (Wait 1962, Frischknecht 1973, Eliassen 1956), only a short discussion of the principles is presented here.

The electromagnetic ground wave field vectors in the far-field of a vertically polarized transmitter are shown in Figure A2. At the ground surface there are three field vectors: the horizontal, radially oriented electric field E_x, the horizontal, azimuthally oriented magnetic field H_y, and the vertical electrical field E_z (x, y, z refer to a local Cartesian coordinate system). All three field vectors decay equally in amplitude with increasing distance from the transmitter. In the ground wave mode the relative amplitudes and phases of these fields at VLF are not influenced by the total path of propagation but only by local resistivity conditions. At distances approaching 1000 km sky mode transmission becomes important. (For the survey discussed in the text, the proximity of the test site to the transmitter (300 km) ensured that only the ground wave was present and hence that there was no possibility of ionospheric interference.)

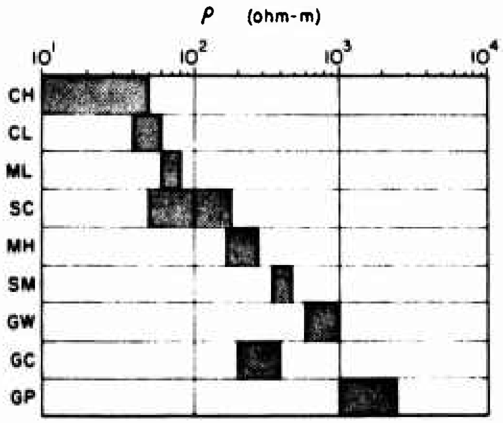
Because of the large refractive index of the ground at radio frequencies, a near vertical wave propagates into the ground with horizontal vectors H_y and E_x. In the ground the amplitudes of E_x and H_y attenuate with depth, and in homogeneous ground the distance over which the field decays to 37% of its surface value is called the skin depth of the radiation. Figure A3 illustrates the dependency of the skin depth on the frequency of the transmitted signal and the resistivity encountered for a homogeneous earth. The skin depth of the radiation is an important parameter, since it approximately indicates the depth to which information is obtained by a measurement at the surface.

Both E_x and H_y are continuous across the ground surface, but E_z becomes negligible in the ground. E_x can therefore be measured by a dipole antenna above the earth's surface or in the ground by measuring the field strength between two probes. H_y is measured by a coil located near the surface, and E_z is measured with a vertical dipole antenna above the ground.

The basis for obtaining a local measurement of ground resistivity is illustrated in Figure A4, where



After Culley et al. (1975).



From Hoekstra and Delaney (1973).

Figure A1. Examples of resistivity ranges for common earth materials. Soil types are described using the Unified Soil Classification System.

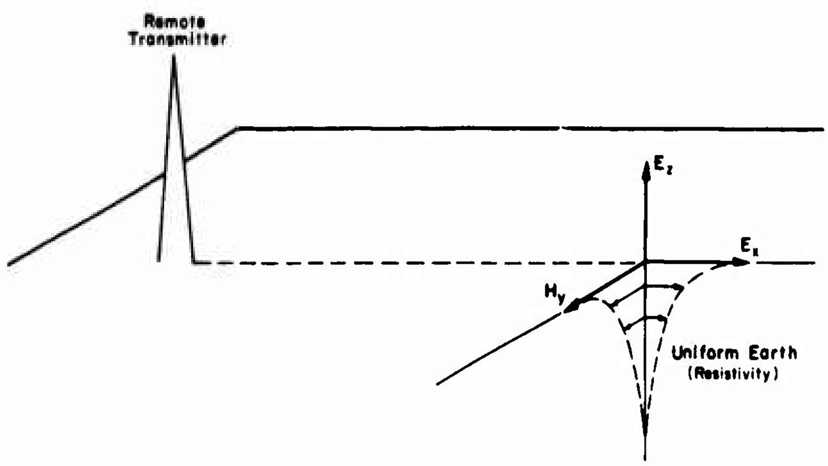


Figure A2. Electromagnetic field components of a vertically polarized radio surface wave.

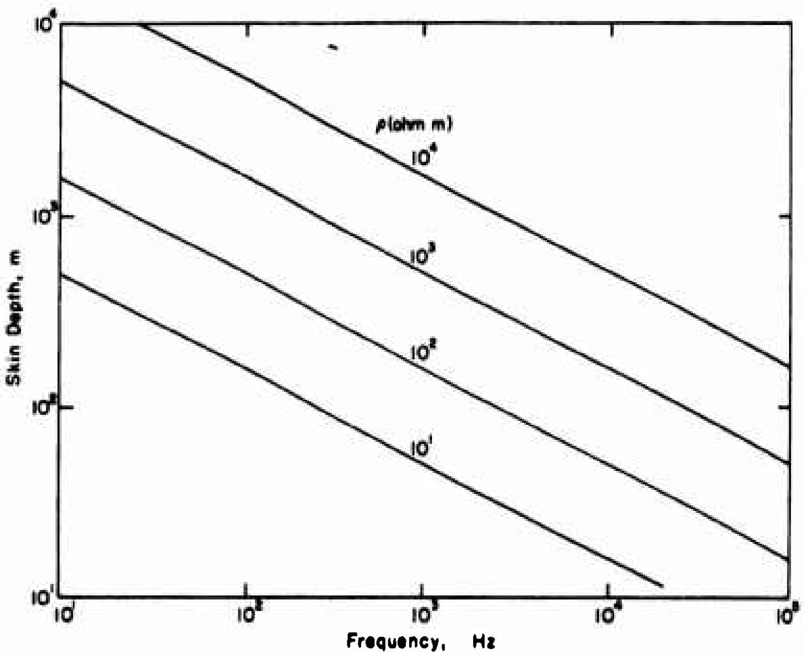


Figure A3. Skin depth of electromagnetic plane waves as a function of frequency with varying ground resistivity ρ.

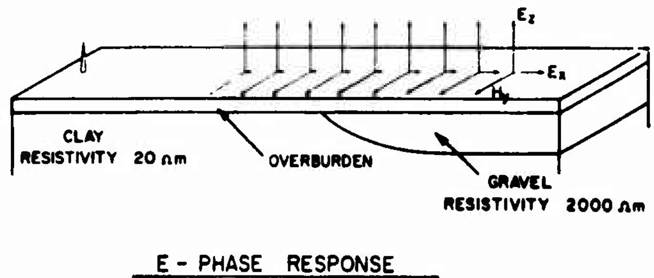


Figure A4. Schematic representation of the local changes in the magnitude of the electromagnetic field vectors of a vertically polarized groundwave when earth materials having different resistivities are traversed.

a wave propagates over a change in ground conditions. Changes in local subsurface conditions cause perturbations in amplitude and phase of E_x, while local changes marginally affect E_z and H_y. Therefore, by measuring the ratio of E_x/H_y (called surface impedance) or E_x/E_z (called wave tilt) a measurement is obtained of the local electrical resistivity.

The computation of ground resistivity, at present, neglects the effects of the permittivity of the ground, and there are circumstances when such procedures may introduce substantial errors (Olhoeft 1975). However, in many applications the delineation of changes in subsurface conditions is the primary object, and a determination of the exact value of ground resistivity is less important.

Over the past decade several schemes for measuring the resistivity of ground from radiowaves by using the principles discussed above have been tried. Two approaches have proven to be practical: a ground-based technique (Collett and Becker 1967), and an airborne technique (Barringer 1972, 1973). The ground technique relies on a measurement of surface

impedance (E_x/H_y), while the airborne method uses the wave tilt phenomenon (E_x/E_z) for plane waves at grazing incidence. For plane waves at grazing incidence over a smoothly layered earth, the two measurements are related by the free space impedance, 377 ohms, as follows:

$$W = Z_s/377$$

where W is the wave tilt and Z_s the surface impedance.

Since Z_s and W are complex quantities, they both have an associated amplitude and phase. The amplitude is converted to "apparent" resistivity by using the formula for a homogeneous earth (Wait 1962) such that

$$\rho_{app} = Z_s^2/2\pi f \mu_0 = W^2/2\pi f \epsilon_0 \qquad \text{(A1)}$$

where ρ_{app} is the apparent resistivity measured in ohm-meters, f the operating frequency in Hz, μ_0 the magnetic permeability of free space and ϵ_0 the free space permittivity. Theoretical modifications in apparent resistivity and phase due to layering of materials with differing resistivities are well documented (Wait 1962). In general when resistivity increases with depth, phases are below 45°, and when resistivity decreases with depth the phases are greater than 45°. Phases of 45° are indicative of uniform resistivity with depth.

For the airborne system only the quadrature value of wave tilt can be measured, because aircraft roll instability causes an in-phase coupling of the vertical field with the (offset) horizontal antenna. Therefore, present data processing assumes an arbitrary phase angle of 45° between E_x and E_z and the computation of apparent resistivity uses the formula:

$$\rho_{app} = W^2/\pi f \epsilon_0 \qquad \text{(A2)}$$

where W = quad (E_x/E_z).

This inability to distinguish the separate effects of phase and amplitude limits the degree of airborne subsurface interpretation. Therefore, it often becomes necessary to conduct preliminary ground studies to determine if the combined effect of phase and amplitude will still allow extensive airborne differentiation of material type.

Ground measurements are performed with the surface impedance (E_x/H_y) technique. The technique must be used for groundbased surveys because E_z is disturbed by vegetation and is therefore an unreliable reference. In the airborne survey it becomes necessary to use the quadrature wave tilt method to eliminate the undesirable coupling mentioned above. In this case E_z is more reliable since the observation is made well above the ground surface, substantially removed from vegetation effects. However, mountain ridges are known to sometimes enhance this reference field (Harrison et al. 1971) thereby depressing the actual resistivity values but not altering regional resistivity patterns, as is discussed in *Results*.

Since the radiation wavelength used is so great (> 15 km at VLF), a flight altitude of 150 m is equivalent to less than 0.01 wavelength. However, the resolution in airborne mapping of resistivity anomalies is reduced, compared to ground measurements.

APPENDIX B. MAGNETIC SURVEYING

Magnetic data are a result of both the intensity of the earth's magnetic field and the magnetic properties of minerals present in the surveyed area. Magnetic anomalies are disturbances in the earth's magnetic field that are caused by changes in the amount and type of magnetic minerals associated with various rock types. The magnetic minerals usually responsible for these disturbances are magnetite, pyrrhotite, ilmenite, and hematite.

Magnetic disturbances present themselves in various ways, such as changes in field direction (usually termed a "dip" or change in declination), and as changes in total field strength or intensity. The most common method of presentation is contouring lines of total magnetic intensity above a background value measured at some reference station. Values are presented in terms of gammas above the reference station value, one gamma being equal to 10^{-5} gauss. The earth's magnetic field varies with position and time of year but generally falls in the magnitude range of 0.5 to 1 gauss. Contours do not necessarily outline a rock formation but can be highly indicative of the rock types present.

Additional information on magnetometer surveying can be found in the texts by Grant and West (1965) and Ward (1967).